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THEORY OF DETONATION SPIN

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[Following is the translation of an article by Ya. B. Zel'dovich entitled "K teorii detonatsionnogo spina" (English version above) in Doklady Akademii Nauk SSSR (Reports of the Academy of Sciences USSR), Vol LII, No 2, Moscow, 1946, pages 147-150.]

(Presented by Academician N. N. Semenov, 11 February 1946.)

Perfectly natural phenomena taking place on propagation of detonation in dilute gaseous miztures, which have received the name "detonation spin", until recently have not been explained.

In the Institute of Physical Chemistry, K. I. Shchelkin, A. S. Sokolik, M. A. Ribin, and the author have in their research progressed in the theoretical and experimental aspects of detonation in gases. The theory of detonation may not be regarded as completed until the phenomenon of detonation spin is explained away. This is why this problem is so important.

The realization that on spin detonation the self-ignition of the explosive mixture does not occur instantaneously in all sections of the tube on the flat front of theshock wave, but occurs at separate points, moving in a helix, is, at the present time regarded as proved (1).

In the work of K. I. Shchelkin (2) isproposed theimportant and fertile thought that the conflagration takes place at the break of the front of the shock wave. As Shchelkin shows, the break of the front of the shock wave on spin detonation may be effectively shown in the photographs of Bone, Fraser, and Wheeler (3). Owing to the correct and fertile representation of thepresence of the break of the wave and of the significance of the break for the spin detonation, Shchelkin's work (2) is a most important milestone in the formulation of the theory of spin detonation. Further development of this theory and, in particular, the considerations stated in this article, should be based on the aforementioned concept of Shchelkin, which first discovered the possibility of rational approach to the mysterious spin

phenomenon.

Shchelkin explains the helical path of the break by the fact that intersecting the inclined surface of the flames formed on the path of the break, compressed gas burns and assumes an angular velocity; the angular velocity of the break is equal to the angular velocity of the gas. One is unable to agree with this part of Shchelkin's work for two fundamental reasons:

1. The motion of the gas burning in the wake of the break does not influence directly the translation of the very flaming break.

2. The angular velocity given to the gas on the intersecting of the flame surface (of the path) should be proportional to the velocity of propagation of burning and, consequently, does not suffice for the explanation of the nature of the observed, with the spin, velocity of rotary motion of the flame point.

A detailed examination of Shchelkin's calculation (formula 2) and the numerical calcualation of the article (2) shows that in the calculation there are definite errors which, after correction, causes the agreement between the calculation and the experiment to disappear.

Accepting Shchelkin' opinion on conflagration in the break, one should look for the fundamental reason, supporting the existence of such a break, causing the displacement of the break down the front of the shock wave (in a cylindrical tube this motion takes place together with the progress of the wave, ensuring the propagation of conflagration in a spiral) and defines the translational velocity of the break.

For this reason the phenomenon of rapid conflagration of the gas in a skew shock wave which forms the break: the amplitude of this skew wave is larger than the amplitude of the basic wave, spreading in the direction of the detonation. This explains why the gas does not ignite in the basic wave, but only in the skew one. The shock wave, after which forllows the rapid conflagration of the gas, represents nothing else but the detonation wave.

Thus, we propose that on spin detonation a plane (strictly speaking, an almost plane) shock wave is at first propagated, a small part of which is changed into a skew detonation wave. As is known, the equations of conservation of mass, momentum and energy give for the detonation products defined a relation between pressure, specific volume and detonation rate. Under ordinary conditions, when one investigates the detonation of the gas in a tube, on the whole, there appears only one defined region, where the pressure of the products is p_B and the minimum detonation velocity is D (compare [4], Fig 1; or [5], Fig 16, point B).

The velocity of the shock wave which spreads in the gas is obviously identically equal to the velocity of propagation of detonation D. Along with this, the pressure p_B is approximately twice

$p_B \cong 2p_S$. These correlations are also valid in the case of spin detonation, considered on the whole (that is, for a progressive [directional] motion of spin detonation), as the unpublished calculations of Ratner and Ditsent, mentioned in the author's book (5), have shown.

The author has first succeeded in proving conclusively that systems at high detonation propagation velocity but small pressure, may not be caught up with while a chemical reactions is in progress (4, 5). The inability to realize under normal conditions regions which would correspond to pressure much higher than p_S, the pressure of detonation products and higher than D velocity, has been shown a long time ago (6, 8); this inability follows from the fact that in this region the sound velocity in compressed gas is higher than the detonation velocity, and because of that, the ensuing state (which we shall call Γ) of detonation products is incompatible with the wave following the detonation wave.

The fundamental idea of the proposed work is contained in the fact that in the skew detonation wave, changing part of the shock wave on spin detonation (see above), creates state Γ. It may form in this case because the detonation products occuring in the skew wave are surrounded by compressed but not reacting gas, whose pressure is $p_B \cong 2p_S$. Thus, one may at first approximation expect that in the skew detonation wave the pressure of combustion products $p_\Gamma = p_B$ shall be reached and, correspondingly, the high detonation propagation velocity D_1. However, the detonation wave is unable to travel forward with this higher velocity D_1, so that state Γ is formed only because of the high pressure of the surrounding gas which propels the plane shock wave with smaller velocity D. If the detonation wave traveled forward it would be deprived of the support of the shock-compressed gas. Therefore, the velocity D is inclined at an angle to the direction of spreading detonation in the bulk (toward the axis of the tube) so that its projection on the axis of the tube is equal to D and the perpendicular component is equal to $\sqrt{D_1^2 - D^2}$.

With this direction of propagation of the skew detonation wave, it does not travel forward and does not lag behind the plane shock wave and simultaneously displaces downwards along the surface of the shock wave.

In a cylindrical tube this displacement takes place along the boundry and describes a helical glowing path, seen on the photograph of the skew detonation wave.

A more critical approach leads to the inevitability of some precise formulation of that scheme. With simultaneous propagation of a plane shock and skew wave of equal pressure $p_\Gamma = p_B$ in one and the same gas, the direction of motion which the gas acquires in these waves is somewhat different, so that the method of first approximation to the kinematics does Not apply. Actually, the skew detonation wave moves at a supersonic velocity relative to the shock-

compressed gas; the detonation products collide with the shock-compressed gas on the forward [See note] edge of the skew wave, when a change in direction takes place in the shock-compressed gas together with the corresponding pressure increase, so that $p_r > p_B$. ([Note:] Forward relative to lateral motion of the skew wave.) At the rear edge of the skew wave, where it also has a boundry with a shock wave, expansion of detonation products takes place so that $p_r > p_B$, and also because at this edge the shock-compressed gas and the detonation products separate instead of colliding. This expansion does not upset the investigated region, provided that in the existent coordinate system, in which is contained the shock and the skew detonation wave, the traveling velocity of the detonation products is equal or exceeds the speed of sound.

From physical considerations we choose the case of equal translational velocity of the combustion products to the velocity of sound in them, when one obtains the maximum p_r and the best conditions of conflagration. The determination of the conditions in toto gives the opportunity of determining quantities of interest to us: pressure p_r, velocity D_1, and the angle between the direction of propagation with the axis of the tube. A numerical example has been worked out in which there was assumed a constant heat content, the adiabatic index k = 1.4, conservation of the number of molecules during reaction, and a low initial temperature in comparison with detonation temperature.

The calculation gives $p_B = 2p_H$; $p_r = 2.75 p_H$; $D_1 = 1.30\ D$; the angle between the planes of skew detonation and the plane shock waves is equal to 20°36'; every wave travels along the normal to its surface, and the line of intersection of the waves translates at an angle of 45°30' to the axis of the tube. The observed frequency of the spiral should correspond exactly to the last angle. Thus, the ideas developed above agree, at least qualitatively, with experimentation. Other hitherto unsolved problems are the exact justification of the above assumed condition of equality of velocity of motion with the sound velocity in combustion products in the skew detonation wave, the explanation of the mechanism of gas combustion, the conflagration "break" (of the skew detonation wave), traveling in a helix, the definition of the dimensions of the skew wave (which we have assumed to be small), and the boundry of existence of spin detonation (from the point of view of transformation into a normal one and from the point of view of attenuation).

However, due to the nature of the problems connected with gas dynamics (at the limiting velocity -- the speed of sound), the here mentioned most interesting quantities (the helix angle and the pressure of the skew wave) is to a large extent independent of the solution of the further problems mentioned here. I should like to express my thanks to L. D. Landau for our valuable discussions.

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